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RUGGEDIZED PRECISION CRYSTAL UNIT FOR AIRBORNE AND MISSILEBORNE FREQUENCY SOURCES

TECHNICAL DOCUMENTARY REPORT ASD-TDR-62-1054

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Elcetromagnetic Warfare and Communications Laboratory
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(Prepared under Contract No. AF33(616)-8100 by
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NOTICES

FOREWORD

This report was prepared by Bliley Electric Company, Erie, Pennsylvania, on Air Force Contract AF33(616)-8100, under Task No. 415606, "Frequency Control Devices," of Project No. 4156, "Electronic Tube Technology." The work was administered under the direction of the Electromagnetic Warfare and Communications Laboratory, Aeronautical Systems Division. Mr. Stanley E. Weber, ASRNCS-2, was project engineer for the Laboratory.

The studies presented began in March 1961 and were concluded in November 1962; they were conducted in the High-Precision Crystal Unit Laboratory of the Bliley Electric Company under the supervision of Mr. J.M. Wolfskill, Chief Engineer, and Mr. R.T. Schlaudecker, Assistant Chief Engineer. Mr. John E. Lawson was project engineer. for Bliley.

This report is the final report and it concludes the work on contract AF33(616)-8100.

ABSTRACT

Currently available high-precision crystal units are not completely satisfactory for use in certain airborne or missile-borne equipment primarily because they cannot maintain the necessary frequency stability while being subjected to environmental disturbances such as high frequency vibration or shifts in orientation.

A specification sheet, Exhibit WWRN 61-11, was prepared to list those requirements which were considered to be necessary or desirable in high-precision crystal units for use in aircraft or missiles. The requirements were deliberately designed to demand advancement in state-of-art techniques. The purpose of this study was to investigate the feasibility of the requirements and to establish realistic degrees of compliance for those requirements where complete satisfaction could not be attained.

As expected, it was not possible to produce crystal units which would meet all of the requirements listed. However, it was possible to comply with most of them and to approach the others much more closely than would be expected from evaluation of conventional high-precision crystal units. Design developments made during this study resulted in significant improvements in performance during shock, vibration, and orientation test conditions.

A brief history of this study is given, tracing the development of the design which was used on the feasibility-model units. A discussion of evaluation equipment and techniques is included because making accurate measurements of crystal performance proved to be the most difficult portion of the work. Design information for the feasibility-model crystal units is presented. Each of the original goal requirements is listed and comments are made on the extent to which each goal is practical at the present state of the art. A recommended specification is presented to outline realistic requirements for high-precision crystal units of this type.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

Increasingly severe demands are constantly being made on frequency control devices which are used in airborne or missile-borne equipment. Improved performance levels are needed to meet these demands. A factor which limits the further development of this equipment is that conventional high-precision crystal units cannot maintain the necessary frequency stability during the vibration and orientation conditions which are encountered in modern aircraft and missiles.

Design and performance requirements for a 5 megacycle, high precision crystal unit suitable for use in aircraft or missiles were listed in WADD R&D Exhibit WWRN 61-11. These requirements were intended to guide advancement of state-of-art techniques and lead to the development of a new high-precision crystal unit capable of withstanding severe environmental hazards. The purpose of the study which is reported here was to investigate the feasibility of the requirements and to establish realistic degrees of compliance for those requirements were full satisfaction could not be attained.

This study was conducted by adaptation of conventional high precision crystal unit designs to the new requirements, fabrication of experimental units, evaluation of these units, analysis of the causes of failures, and re-design and re-evaluation as necessary to achieve optimum designs. The major obstacle which hindered this program was that available evaluation equipment could not measure crystal unit performances accurately in many of the prescribed tests. In particular, much difficulty was encountered in controlling operating temperatures of crystal units with sufficient accuracy so that temperature fluxuations did not distort performance data.

Improvements were made in evaluation equipment and techniques during this project, but the inability to make more accurate measurements is still the limiting factor which prevents the further development of these crystal units. Despite this handicap the design derived for the feasibility-model crystal units of this project is definitely superior to that of any available high-precision crystal unit with respect to ability to withstand shock, vibration, and orientation test conditions.

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II. GOALS OF THIS PROGRAM

The basic intent of this program has been to develop a design for 5 megacycle, high-precision, quartz crystal units which would be similar to conventional high-precision units (such as the CR-71/U listed by specification MIL-C-3098C) but which would provide superior frequency stability during the environmental conditions which are encountered in aircraft and missiles. In addition to this basic purpose it was also desired that state-of-art techniques should be advanced so that improvements could be made in the electrical qualities of the new units, particularly with respect to operation at higher temperatures. The following table lists the major differences between the requirements for the CR-71/U units and the goal-requirements for these new units:

IMPORTANT DIFFERENCES: CR-71/U REQUIREMENTS AND THE GOALS LISTED FOR THIS PROGRAM

REQUIREMENT	CR-71/U UNIT; (MIL-C-3098/49)	GOAL REQUIREMENTS
operating temperature	+71°C area (± 6°C tolerance)	+90°C area (± 2°C tolerance)
tolerance on nominal frequency (calibration)	$\pm 8 \times 10^{-7}$	$\pm 1 \times 10^{-8}$
static capacitance	4.0 ± 10% pfd	3.5 ± 10% pfd
vibration:		
test	10 to 150 cps, 10G	10 to 1000 cps, 10G
requirement (freq. stability)	$\pm 1 \times 10^{-7}$	$\pm 1 \times 10^{-9}$
orientation:		
test	shift from any attitude to any other attitude	same
requirement (freq. stability)	$\pm 1 \times 10^{-8}$	$\pm 1 \times 10^{-10}$
acceleration:		
test	none	10G, three minutes
requirement (freq. stability)	none	$\pm 1 \times 10^{-9}$

III. STATE OF THE ART

The CR-71/U units, the only standard military crystals which are directly comparable to the new units envisioned by this program, have several physical and electrical characteristics which are similar to the goal requirements set up to guide this investigation. The frequency area is the same for both units, the resonator type and the mode of operation are identical, and the specified holder is compatible with the standard package. Effective resistances, load capacitances, and drive levels are directly comparable, and such factors as calibration, shunt capacitance, aging performance, and vibration and orientation requirements are similar on both units, even though the new goals are more stringent than the CR-71/U requirements. It would appear, superficially, that minor modification to the CR-71/U design and improvements in processes and techniques might serve to satisfy the new goals. There are, however, three areas in which the new units differ significantly from the conventional units, and in each of these areas the new requirements necessitate advancements in the state of the art.

First, the higher operating temperatures specified for the new units (nearly 20°C higher than those of CR-71/U's) impose many problems. Crystal unit performances deteriorate increasingly as operating temperatures are increased; in fact, much of the recent development work in this field has been directed toward lower operating temperatures to avoid the problems which arise with the higher temperatures: effective resistances increase, frequency aging rates are accelerated, and the slopes of the temperature coefficient curves become so much steeper that providing adequate temperature control becomes very difficult. It could be expected that design and fabrication of the new crystal units would be much more difficult than if the units were to operate at lower temperatures.

Second, the stringent vibration and orientation test conditions and requirements for the new units greatly exceed the performance capabilities of the CR-71/U design; it had already been established that the design was approaching its ultimate capabilities in meeting the CR-71/U requirements.[1] In addition, it was known that the plano-convex resonator design (contoured only on one face surface) used on the CR-71/U units was not capable of providing the degree of frequency stability in the orientation test which could be supplied by a bi-convex design

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[1] Completion Report for Step I, Industrial Preparedness Study on Ruggedized 5000 Kc High Precision Crystal Units. Bliley Electric Co., Erie, Pa. for the U.S. Army Signal Supply Agency, Philadelphia, Pa. Contract DA-36-039-SC-54697. December 1960.

(contoured on both face surfaces.)[2] Because of the stringent requirements specified for the new units it could be assumed that they would need both a new mounting arrangement and a bi-convex crystal resonator.

Third, the performance levels prescribed for the new units are so much more exacting than those imposed on the CR-71/U units that new equipment and new techniques are obviously needed to evaluate performances to the levels of accuracy specified. Not only is this true in connection with the frequency-stability measurements, where an ultra precise frequency standard and special ultra high-frequency multipliers are necessary, but it is also true in connection with the temperature control devices (ovens) which are needed to make frequency readings on the new units. (The +90°C area operating temperatures of the new units are well above the control range of conventional ovens, particularly in view of the very stringent temperature control requirements.) There could be no doubt that development of measurement equipment and evaluation techniques would be necessary as well as development of a new unit design.

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[2] W.L. Smith, An Ultra-Precise Standard of Frequency: Final Report. Bell Telephone Laboratories for the U.S. Army Signal Research and Development Laboratories, Fort Monmouth, New Jersey. Contract DA-36-039-SC-73078. December 1960.

IV. DEVELOPMENT OF THE NEW DESIGN

Many of the goals set up for the new units were so exacting that available frequency equipment could not evaluate experimental units. This was obviously true in connection with such stringent performance requirements as the ± 1 part in 10^{10} stability demanded in the orientation test; special equipment is necessary to make measurements at this order of accuracy (± 0.1 cycle per second at the 1000 megacycle level.) However, it was also true in connection with many of the seemingly-less-demanding requirements where conventional measurement equipment could have served if adequate temperature-control ovens had been available.

At the time when the development work on the new units was scheduled to start none of the equipment needed to make accurate frequency stability evaluations was yet in operation. In fact, it was found that no meaningful measurements of performance could be made because available ovens could not provide sufficient stability at the +90°C operating temperature areas. Preliminary experimentation quickly demonstrated that perfecting equipment and techniques to measure performance accurately was going to be a lengthy and painstaking process. In an attempt to expedite the project it was decided to start the derivation of the mounting arrangement for the new crystal unit design without waiting until the performance-measurement equipment was ready.

This approach, which tended to separate the physical structure of the unit from its electrical performance, was considered to be feasible only because empirical knowledge of high-precision crystal unit designs has set up certain standards which, it was believed, could guide the development of the crystal mounting arrangement even without the benefit of simultaneous investigation of the electrical performance characteristics. For example, it is known that a crystal mounting arrangement must be free from resonant movements during the environmental disturbances in which it is expected to maintain frequency stability; there is a direct relationship between the magnitude of any resonant movements and the extent of any frequency excursions. Experience has shown that most of the movements which result in frequency excursions can actually be seen, under 10X magnification, if the units are examined while being subjected to the environmental disturbances. (A stroboscope is used to assist in this examination.)

It was hoped that many of the details of the mounting arrangement for the new units could be worked out using visual observation of experimental units during vibration as a means of evaluation. It was expected, of course, that this method would quickly be supplanted by actual measurements of performance. However, despite many attempts at making such measurements, the project was quite far along before accurate and reliable measurements were finally achieved. For this reason the structure and assembly

of the feasibility-model units was derived prior to, and almost independently of, frequency stability measurements. As a result, the crystal mounting structure is undoubtedly more sturdy than would appear from the performance ratings which are listed for the feasibility-model units. The fact that the units have been underrated stems directly from the limited ability to make accurate measurements of performance; in most cases the performance ratings have been established by the ability to make evaluations rather than by the performance capabilities of the units. The mounting itself, evaluated by observation, was not penalized by these measurement limitations.

Derivation of the mounting arrangement for the new units was started by review of the assembly of military-type CR-71/U units. The CR-71/U's, described by government specification MIL-C-3098C, are high-precision, 5 megacycle crystal units. They are the only standard crystal unit type which can be compared directly to the new units envisioned by this program; many of the CR-71/U performance requirements are similar to the goals set up for the new units although, of course, the CR-71/U requirements are much less demanding, particularly since the CR-71/U units are designed to operate at temperatures a full 20°C below those specified for the new units.

Figure 1, page 7, shows the assembly of a CR-71/U unit. Note that the plano-convex, AT-cut quartz resonator, designed to operate on the fifth overtone mode, is supported vertically by two wires. These wires are soldered to fired-silver spots on the edge of the resonator and are attached to rods embedded in the glass platform. The glass platform is the main support unit of the mounting assembly. It is attached rigidly to rods embedded in the glass header and, in addition to giving rigidity to the entire structure, the disc serves as a barrier to protect the gold-plated crystal from heat and contamination during the flame-sealing operation which joins the flared header to the enclosing envelope.

In the CR-71/U mounting the limber wires which attach the crystal to the glass platform were not designed to give the maximum possible support but rather were intended to cause the least possible interference with the operation of the resonator. (Despite the need for support, care must be used to avoid mountings which restrict or strain the resonator since such arrangements distort performances.) At the time the CR-71/U design was formulated the primary concern was to obtain the best possible performance under optimum operating conditions and there was no intention of subjecting these units to environmental disturbances, even such as those now listed in the CR-71/U specification. (The capability of this design for these conditions was established later, by subsequent evaluation.)

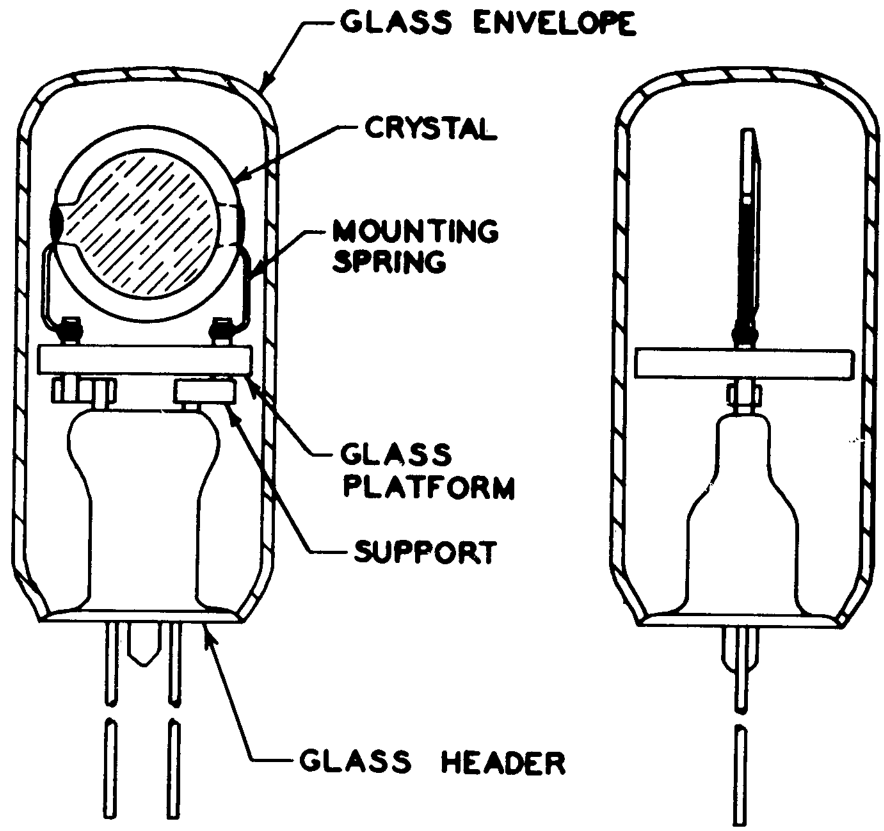

FIGURE 1

ASSEMBLY DRAWING OF CR-71/U CRYSTAL UNIT

When the need for a unit which could withstand environmental disturbances (such as shock, vibration, and orientation shifts) first became apparent, a more rugged version of the high-precision, 5 megacycle unit was developed. The rugged unit, known as the CR-(XM 7)/U, was expected to serve as the prototype for the present CR-71/U design. However, the same evaluation program which proved that the original design was capable of meeting the CR 71/U specification also established that the CR (XM 7)/U design was capable of better performances than those for which it had originally been rated. (Both designs had been initially underrated because of the difficulties in making accurate evaluations.)

The differences between the original unit and the rugged version were entirely in the manner in which the crystal was mounted. The original design had used the vertical mounting with its two-point support while the rugged unit used horizontal support. The vertical-mount design is easier to fabricate and yields are higher; there is no benefit from the more-difficult horizontal mounting except in such environmental conditions as shock, vibration, orientation, etc. For this reason the vertical mount is preferred for those applications where it can meet the specific needs and the horizontal mount is used only when superior performance in environmental tests is needed. It was obvious, however, that the horizontal mounting of the CR-(XM-7)/U design was better suited to the needs of this program than the vertical mounting of the standard CR-71/U units. Accordingly, attention was turned to the CR-(XM-7)/U design.

Figure 2, page 9, shows the assembly of a CR-(XM-7)/U unit. Note that the crystal resonator is mounted horizontally by three nickel ribbons which attach the crystal to the parallel platform. The three ribbons are spaced at 90° intervals along the circumference of the crystal plate, leaving one section unsupported. This arrangement is desirable in that it provides a combination of good support with minimum interference to the resonator. The first experimental units for this program were made with this mounting arrangement. In fact, these first experimental units were identical with the CR-(XM-7)/U except that the ZZ' orientation of the crystal plates was shifted upward to provide zero-temperature-coefficient points in the +90°C area.

Many problems were encountered in evaluating these first units and complete evaluation was never accomplished. In fact, the main value of these units was that they helped to locate the problems which prevented accurate evaluation. However, they did serve to show that such parameters as resistance, capacitance, temperature coefficient, and drive level requirements could be met (or closely approached) despite the high operating temperature. In addition, stroboscopic examination of units during vibration disclosed that slight movements of the unsupported edge of the

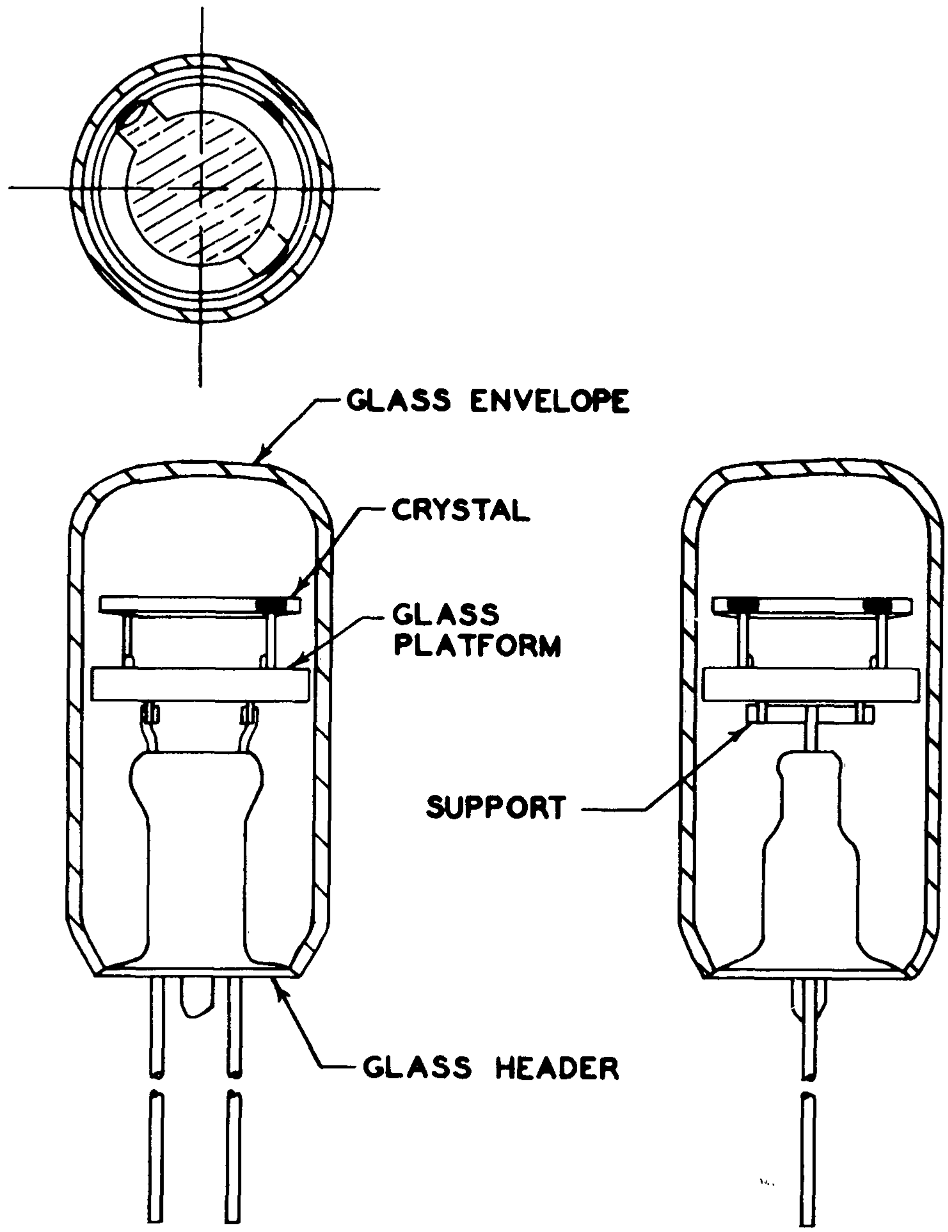

FIGURE 2

ASSEMBLY DRAWING OF CR-(XM-7)/U CRYSTAL UNIT

crystal plate could be seen at about 750 cycles per second, with evidence of resonances in the mounting structure at that frequency. Considerable experimentation was done by using various combinations of ribbon length, width, and thickness in an attempt to eliminate the movement of the crystal but no satisfactory combination was found and a fourth ribbon, to support the previously-unattached edge, was reluctantly adopted.

The fourth ribbon, while desirable from a support standpoint, was expected to impose penalties in performances and yields because of the additional restriction it imposed on the resonator. This has not proved to be true to the extent expected, although there are, of course, some additional penalties in yields and some additional painstaking work involved in the fabrication of units which use the four-ribbon arrangement.

Further observation of experimental units which used the four ribbons, evenly spaced along the circumference of the crystal plate, disclosed, under certain conditions, very small movements of the crystal-platform assembly, as a unit. It was found that these minute movements were possible because of movements of the rods to which the supports for the glass platform were welded. T-shaped supports were substituted for the strips which are used in the CR-(XM-7)/U design and these seemed to eliminate the resonances.

The mounting arrangement for the new units remained at this state of development for quite some time, until additional evaluation of completed sample units disclosed that the T-supports provided freedom from resonances only in one direction and that additional rigidity was needed in the perpendicular direction. Special, gold-plated centering springs, which fit over the edge of the glass platform and firmly contact the enclosing glass envelope, were added to provide the additional support. This final modification provided a crystal mounting arrangement which is free from visible resonant movements through the 10 to 1000 cycle per second vibratory range, sturdy enough so that 100 g shock does not cause significant movements, and sufficiently symmetrical so that shifts in orientation cause few changes in the stress pattern which the mount imposes on the crystal resonator.

Figure 3, page 11, shows the assembly of a feasibility-model unit which uses the new mounting arrangement. (Note that this unit also uses a bi-convex crystal; the superiority of the bi-convex design in orientation testing was demonstrated later, after the mounting system had been adopted.) Figures 4, 5, and 6, pages 12, 13, and 14, shows details of the assembly. A list of the materials and components used to fabricate the feasibility-model units is presented by Table I, page 15.

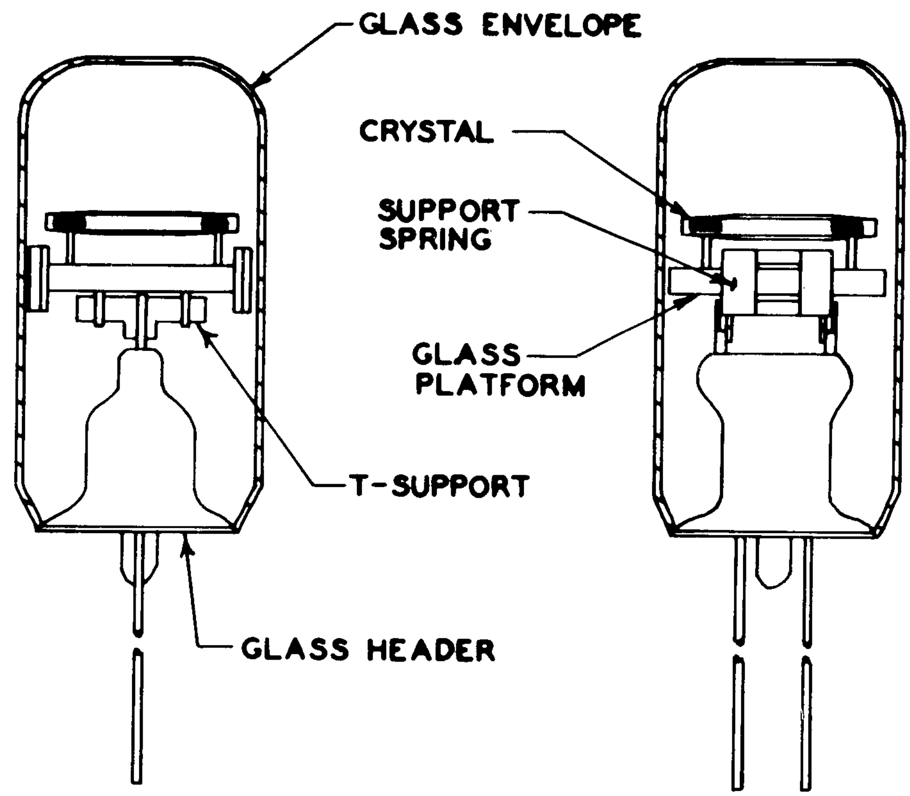

FIGURE 3

ASSEMBLY DRAWING OF FEASIBILITY
MODEL CRYSTAL UNIT

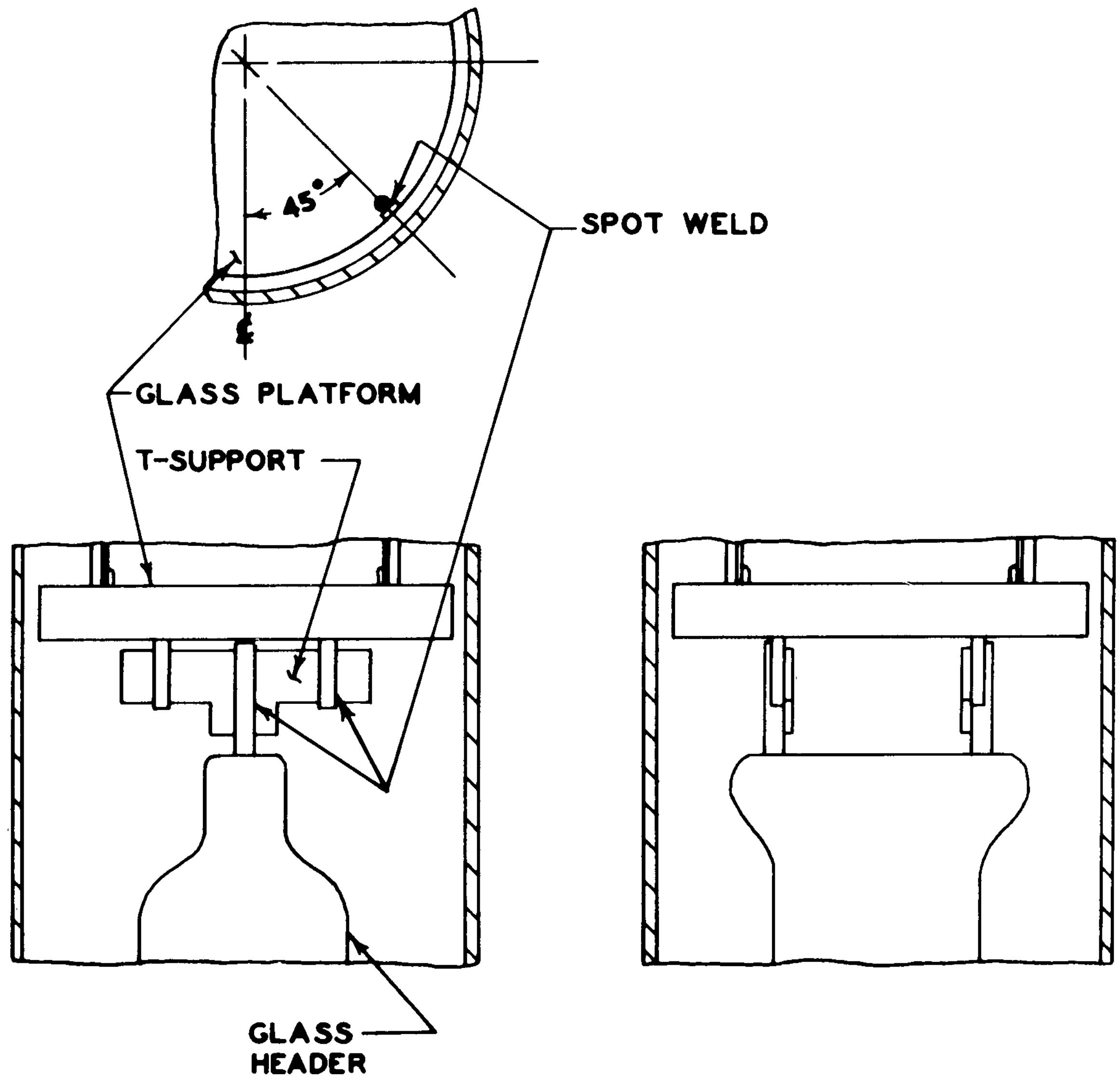

FIGURE 4

DETAIL SHOWING GLASS PLATFORM
MOUNTED ON GLASS HEADER

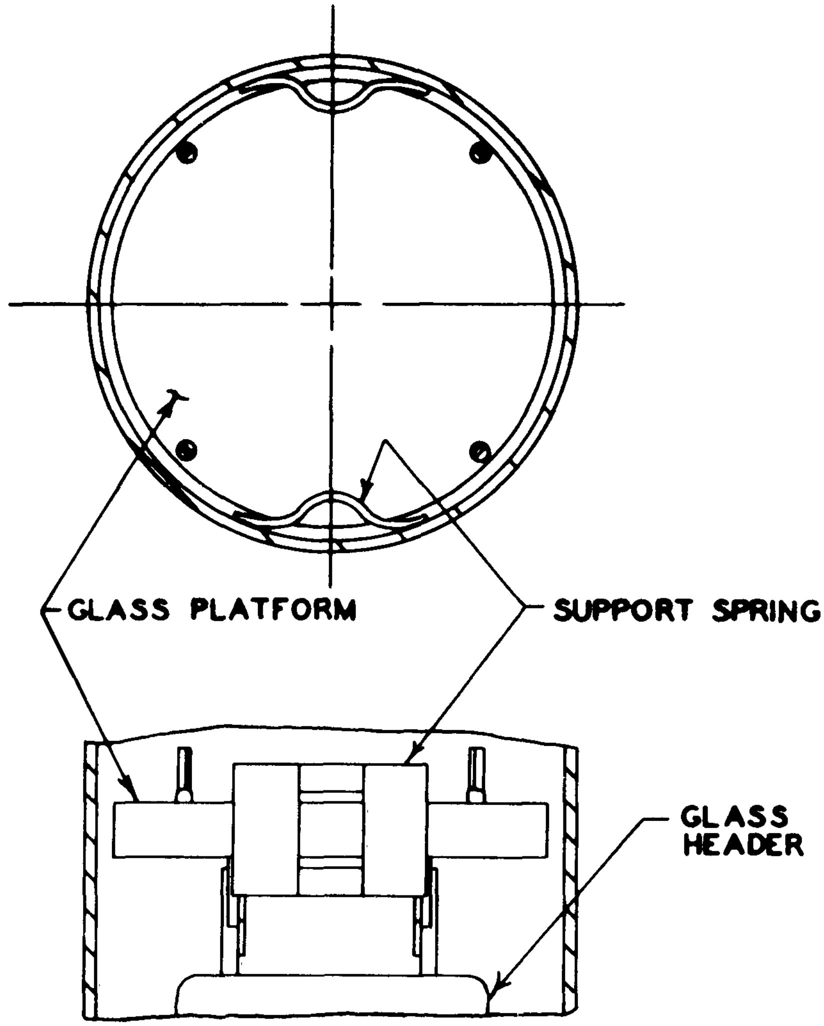

FIGURE 5

DETAIL SHOWING SUPPORT SPRING
ON GLASS PLATFORM

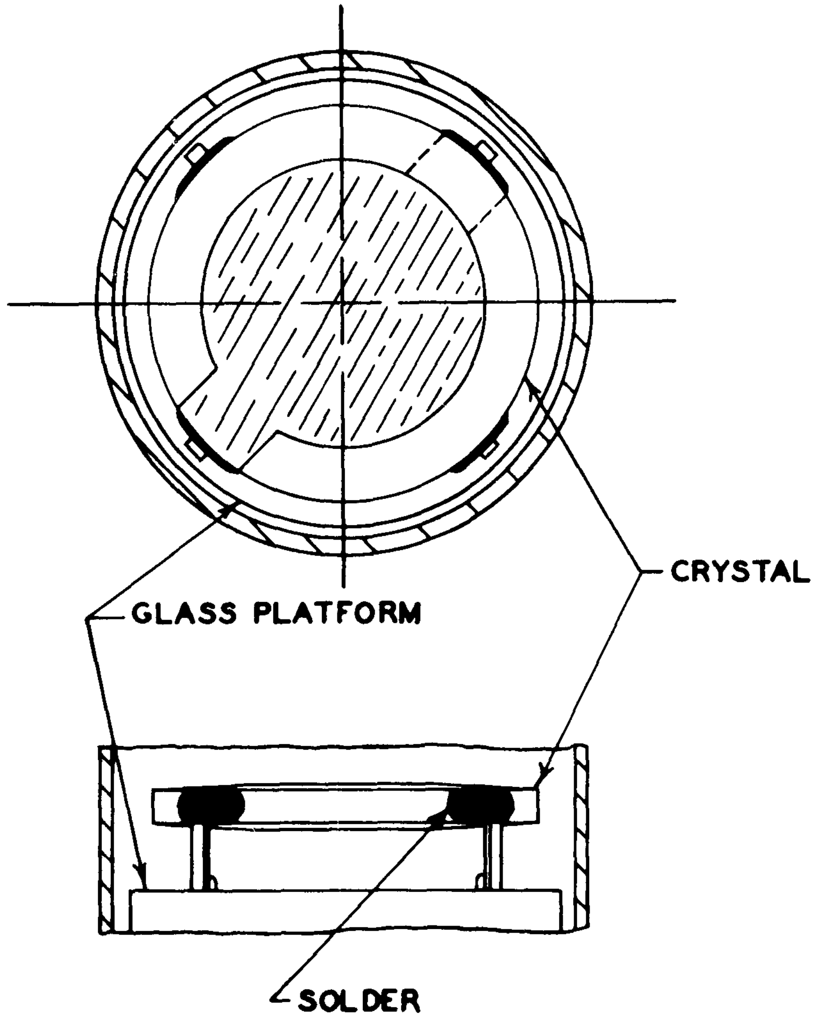

FIGURE 6

DETAIL SHOWING CRYSTAL MOUNTED
ON GLASS PLATFORM

TABLE I

LIST OF MATERIALS

The following is a list of materials and components which were used to fabricate the feasibility-model crystal units. Details of the assembly of these units are shown by Figures 3, 4, 5, and 6.

(1) Quartz resonator: Natural quartz disc, AT-cut. 0.590" diameter, 0.074" thick. ZZ' orientation 35°27.5' ± 0.25'.

(2) Contour: 4.5 diopter, both faces.

(3) Finish: Barnesite polish, after etching.

(4) Silver spots: Hanovia #150 Silver Paste, fired at 545°C.

(5) Electrodes: Evaporated gold, 0.430" diameter with 0.125" "tails"

(6) Support ribbons: Pure nickel strip; 0.003" thick, 0.030" wide, approx. 0.140" long.

(7) Glass platform: Solid glass disc; 0.090" (max) thick, 0.625" diameter. Four 0.020" Kovar support wires embedded 90° apart, protruding both above and below the disc.

(8) T-supports: Pure nickel strip, 0.010" thick, approx. 0.070" wide and approx. 0.5" long.

(9) Support springs: Beryllium copper, spring tempered. 0.005" thick. Gold plated.

(10) Glass header: T 5 1/2 flared stem header; two wire leads.

(11) Glass envelope: T 5 1/2, electron tube type.

Development of the resonator design for the new units was severely hampered by the lack of adequate means by which performances could be evaluated. The situation was most severe in connection with the orientation requirement and remained long after the special frequency-measurement equipment was in operation. Primarily a temperature control problem, the difficulty still was present after special ovens had been developed specifically for the testing of these new units. These ovens, which could be adjusted to within about 0.2°C of any desired operating temperature in the +90°C area and which would control within about 0.01°C of this selected temperature, used external, mercury-relay controllers. The controllers were extremely sensitive to physical disturbances and had to be isolated from the ovens which, of course, had to be subjected to the same test conditions as the crystal units since all measurements had to be made with the crystals at operating temperature. Long cables had to be used to connect the ovens to their controllers and the inevitable disturbances of these leads affected the performance of the ovens sufficiently to cause erratic frequency shifts larger than 1 part in 10^9.

This amount of error, of course, prevented evaluation for compliance with the requirement of 1 part in 10^{10}. Nevertheless, comparison of experimental units which used plano-convex resonators with those which used bi-convex resonators seemed to indicate that the double-contoured version was more stable during orientation testing. This conclusion was in agreement with the findings of earlier investigations and it was decided to adopt the bi-convex resonator for use in experimental units.[3]

The bi-convex configuration is definitely more difficult to produce successfully than the plano-convex shape because the double-contour design retains no flat face surface by which ZZ' (Phi) orientation references can be preserved. This increases the loss due to "angle shifting" (wide variation in the zero-temperature-coefficient points of crystal resonators with identical orientation, similar to the effect which would result from a variety of ZZ' angles) and also demands more care in processing since two surfaces must be contoured. Despite these drawbacks the choice of the double-contour design has proved to be well worthwhile: the feasibility-model units have proved to be capable of providing at least 10 times better frequency stability in orientation tests than the CR-71/U units. (This evaluation has been restricted by the accuracy with which measurements can be made; it is believed that re-evaluation with better equipment will indicate that even higher stability can be maintained by these units.)

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3 A.W. Warner, An Ultra-Precise Standard of Frequency: Ninth Interim Report. Bell Telephone Laboratories for the U.S. Army Signal Research and Development Laboratories, Fort Monmouth, New Jersey. Contract DA-36-039-SC-73078. January 1959.

Eventually our search for better ovens lead us to obtain special transistorized, proportional-control ovens, similar to those used in modern airborne frequency standards. These transistorized ovens proved to be more accurate and much more reliable than the mercury-relay type which were used earlier, particularly when the transistor circuitry was protected from shifts in ambient temperature by a separate temperature-control arrangement. The primary advantage of the transistorized ovens was that they were not significantly affected by movement or by disturbances of the leads which connected the ovens to the control circuits. With these ovens it became possible, for the first time, to take advantage of experimental units. The measurement equipment used is identified and described in the following section.

V. DIFFICULTIES IN EVALUATING UNITS

Figure 7, page 19, presents a block diagram of the UHF measurement arrangement which was set up to evaluate the performances of experimental units. (The equipment used in this setup, together with the other equipment used in evaluating experimental units, is identified by Table II, page 21.) Note that the UHF arrangement shown by Figure 7 was designed only to monitor frequency stability, not to measure frequency. Also note that because of the stringent performance requirements this system takes advantage of the best equipment available so that the highest possible accuracy can be attained.

In this evaluation method the crystal unit under test, controlled at its zero-temperature coefficient temperature by one of the special ovens, is operated with an AN/TSM-17 test set. The frequency of the crystal is multiplied, by special multipliers, to the 1000 megacycle level, where it is mixed with the 1000 megacycle signal obtained by similar multiplication of the output of a primary frequency standard. The audio frequency difference between the two 1000 megacycle signals is amplified, filtered, then monitored with a frequency counter. (A digital printer and a chart recorder provide means to record performances.) A change of 0.1 cycle in the audio frequency established for any unit signifies a change of 1 part in 10^{10} (0.1 cps at 100 mc.)

The measurement accuracy provided by the UHF arrangement is, of course, much less than the 1 part in 10^{10} resolution which it theoretically provides. A basic problem is that the system is based on the comparison of the crystal frequency and a reference frequency and there is no method of detecting whether a change in the audio frequency is the result of a shift in the crystal frequency or whether it is the result of a change in the reference frequency. Both an Atomichron and a Borg Standard were used in the UHF measurement system; the best stability pattern achieved when measurements were made against the Atomichron was about 5 parts in 10^{10}, while a pattern of about 3 parts in 10^{10} could be achieved by the same crystal, under the same conditions, when measurements were made against the Borg. (Fifty-minute test periods were used for the comparisons.)

Some portion of the instability mentioned above was undoubtedly a result of minute variations in the operating temperature of the crystal unit (temperature changes of less than 0.01°C can be very disturbing when measurements are being made in parts in 10^{10}) and such other factors as variations in the ambient temperature on the test set and variations in line voltage also detract from the accuracy. (It was not always possible to control these as closely as was desirable under actual testing conditions.) In addition to the errors introduced by these causes, the frequency counter itself is accurate only to plus or minus one count ($\pm$ 0.1 cps in this system) so that it is doubtful if the actual measurement accuracy was much better than 1 part in 10^9.

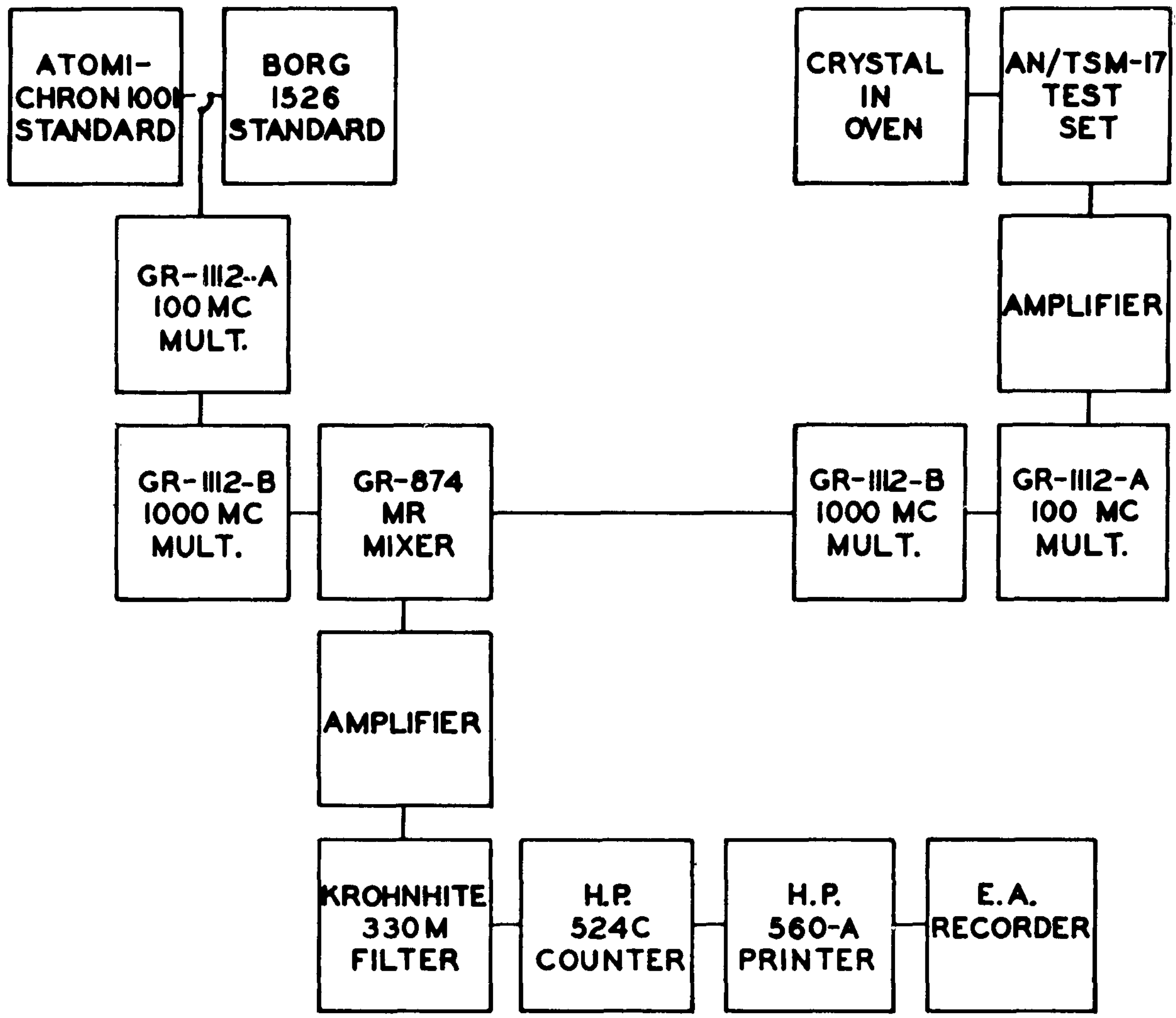

FIGURE 7

FREQUENCY STABILITY MEASUREMENT SETUP
USED TO EVALUATE EXPERIMENTAL UNITS

Another factor which further reduced the accuracy of the evaluations was that in many of the tests the UHF equipment could not be used. The reason for this was that the entire UHF system was rack mounted in a special room, away from the environmental test equipment. (This separation was desirable to help minimize the disturbances of the sensitive UHF equipment.) Since neither the UHF equipment nor the environmental test equipment (such as the vibration test setup) were portable it had been planned to use cables to conduct the signals from the units in environmental testing to the UHF measurement equipment. Unfortunately, it was never possible to use this method successfully, primarily because of errors introduced in transmitting the signals between the two rooms. For this reason most of the environmental test performances could be measured only to the accuracy provided by multiplication of the crystal frequency to the 100 megacycle level and reading it directly on a high-frequency counter. (Accuracy of only about 2 parts in 10^9 can be obtained.)

Measurement problems also prevented performance of the acceleration test which is included among the goal requirements for this program. No centrifuge equipment was available to perform this test but it was proposed that it could be done by some outside laboratory where the necessary test and measurement equipment were available. However, it was not possible to arrange for this, since no commercial laboratory with both the centrifuge and adequate frequency measurement equipment could be located. Troubles with temperature control equipment also complicated the performance of this test for by the time the new ovens were available there was not sufficient time remaining in the schedule to permit arrangements for testing in an Air Force Laboratory.

Despite the fact that the acceleration test was not performed on feasibility-model units, extensive testing for shock, although not included in the requirements for the new units, has shown that the new design is capable of withstanding much more severe shocks than either the CR-71/U or the CR-(XM-7)/U units. This, combined with the good performances of the feasibility-model units in the orientation test (which has a direct relationship with performance in the acceleration test), lead us to believe that the new design is capable of approaching the goal requirement for acceleration.

TABLE II

TEST EQUIPMENT

(1) Test set: AN/TSM-17 (Special 5 Mc high precision crystal unit test set; Radio Frequency Labs, Model 991.)

(2) Voltmeter: Ballantine Vacuum Tube Volt Meter, Model 314.

(3) Crystal ovens: Bliley constructed; transistorized proportional control ovens. Capable of at least 0.01°C stability and adjustable to control within 0.1°C at any point in the range from +88°C to +92°C.

(4) Reference standard: (a) Atomichron Model 1001 (Modified).

(b) Borg Frequency Standard, Model 1527.

(5) Amplifiers: (a) Bliley constructed (used to amplify the signal from the test set before multiplication.)

(b) Bliley constructed, transistorized. (Used to amplify the low frequency signal from the mixer.)

(6) Frequency multipliers: (two complete sets) (a) General Radio Type 1112A (5 Mc to 100 Mc)

(b) General Radio Type 1112B (100 Mc to 1000 Mc)

(7) Frequency mixer: General Radio Type 874 MR

(8) Adjustable filter: Krohn-Hite Filter, Model 330M.

(9) Frequency counters: (a) Hewlett-Packard Type 523DR.

(b) Hewlett-Packard Type 524D.

(10) Digital printer: Hewlett-Packard Type 560A.

(11) Chart recorder: Esterline-Angus Model AW.

(12) Vibration equipment: Complete set MB Vibration Equipment, Model T 112531, with automatic controls.

TABLE II (Con't)

(13) Shock tester: Jolta Model 1001 (meets MIL-STD-202B.)

(14) Orientation equipment: Bliley constructed positioning jig. (Provisions to duplicate previous attitudes.)

(15) Standard crystal unit evaluation equipment: Assorted laboratory and electronic test equipment needed to perform the tests listed by Table I of MIL C 3098C.

VI. EVALUATION OF THE NEW DESIGN

Each of the goal performance requirements for this program is quoted and comments are made on the extent to which each of the requirements is practical at the present time. In those instances where the requirements are not realistic the reasons are presented and specific recommendations are made as to practical specification requirements.

REQUIREMENT:

> 3.4.1 Frequency.- Crystal units developed under this exhibit shall be designed to operate at anti-resonance into a load capacitance of 32.0 ± 0.5 uufd on the fifth mechanical overtone mode of the fundamental frequency of the plate. The output frequency of the units shall be five (5) mc/s.

COMMENT:

> No difficulty in complying with this requirement.

REQUIREMENT:

> 3.4.2 Resonance Resistance.- Resonance resistance shall be 175 ohms maximum, 100 ohms minimum.

COMMENT:

> No difficulty meeting this requirement although there is some penalty in yields because resistance increases sharply in the +90°C area so that many units which would be satisfactory at lower temperatures must be rejected. (See "operating temperature.")

REQUIREMENT:

> 3.4.3 Operating Temperature.- The operating temperature shall be the point of zero temperature coefficient as determined by the manufacturer for the individual crystal unit. The operating temperature shall be 90° ± 2°C. Each unit shall be marked with the operating temperature to one decimal point (e.g. 90.2°C), on the glass envelope.

COMMENT:

> This requirement, while not in itself difficult to meet, is a serious handicap. The +90° ± 2°C operating temperature imposes serious problems and results in lower yields at several points:

(1) Resistance.- Activity is lower at +90°C than at lower temperatures. Approximately 25% of all the final-design units fabricated for this project were rejected because of too-high resistance values, as compared to 10% or less rejects when units are designed to operate at lower temperatures. The maximum point for which units can be designed without penalties in activity is near +85°C.

(2) Temperature Coefficient.- The slopes of the temperature coefficient curves of overtone mode AT crystals become progressively steeper and the "flat" portions of the curves become progressively narrower as the crystals are made to achieve zero temperature coefficient points (operating temperature points) at higher temperatures. In the +90°C operating temperature region most crystals have temperature coefficient changes of 4 parts in 10^8 per degree or more.

(3) Aging.- It is well known that high temperatures cause more severe aging problems; units age tested at +90°C area temperatures do not perform as well as identical units tested at +75°C. The +90°C area operating temperatures imposed by WWRN 61-11 make it impractical to attain the aging stability demanded by WWRN 61-11.

(4) Testing.- Conventional crystal ovens will not provide adequate control at +90°C area temperatures to permit accurate evaluation of these units; control of at least 0.01°C is needed. In addition, the ovens must be adjustable so that units can be operated within at least 0.5°C of the optimum operating point and closer correlation is desirable. Testing was completely stalled until special ovens capable of the required performance could be procured.

RECOMMENDATION:

It is recommended that operating temperatures be below +85°C maximum and that the permitted range of operating temperature points be at least ± 4°C.

REQUIREMENT:

3.4.4 Temperature Coefficient.- Temperature coefficient at a point above the operating temperature by 1°C ± 0.5°C also below the operating temperature by 1°C ± 0.5°C, the temperature coefficient slope shall be not greater than ± 1 part in 10^8 per degree C.

COMMENT:

At the present state of the art it is not possible to control the slope of the temperature coefficient curve directly. Slopes become steeper as ZZ' orientation is shifted to give zero temperature coefficient points at higher temperatures and become flatter when crystals are designed to operate at lower temperatures. The feasibility model units produced for this project had values around 4 parts in 10^8 per degree centigrade. However, it is difficult to measure the exact slope of the temperature coefficient curve, particularly in a production situation where the amount of time which can be spent on any one unit is limited. For this reason a wider tolerance is recommended for a realistic specification.

RECOMMENDATION:

The temperature coefficient requirement should be set at ± 5 parts in 10^8 per degree, at points one degree above and one degree below the turning point.

REQUIREMENT:

3.4.5 <u>Tolerance on Specified Frequency</u>.- The frequency shall be within 1 part in 10^8 at operating temperature.

COMMENT:

Calibration cannot be correlated this closely to final frequency partly because calibration is done at series resonance (to facilitate measurements in the equipment) while final measurements are made at anti-resonance, and partly because it is not possible to control the temperature in the plating chamber with sufficient accuracy. Then, too, there is an unpredictable frequency change which occurs during the flame sealing of the glass envelope. It is possible to calibrate to within 1 part in 10^7 but the time required is prohibitive and the yield is not good. In addition, the fact that correlation between manufacturer's measurements and customer's end use equipment is not usually good enough to take advantage of such calibration must also be considered.

RECOMMENDATION:

A calibration tolerance of ± 5 parts in 10^7 is possible if needed; ± 1 part in 10^6 more practical if actual production is contemplated.

REQUIREMENT:

3.4.6 <u>Drive Level</u>.- Drive level shall be 70 ua ± 20%.

COMMENT:

There is no difficulty with this requirement as long as it is noted that the 20% tolerance applies to the initial setting and that the drive level, once established, must be maintained within about 5% if optimum stability is to be obtained.

RECOMMENDATION:

A drive level requirement of 70 ua ± 20% is practical.

REQUIREMENT:

3.4.7 <u>Permitted Frequency Change Due to Drive Level Variations</u>. Frequency change due to drive level variations shall be no greater than 1 part in 10^9 per 1 db current change over the range 56 to 84 ua.

COMMENT:

The sturdy, ruggedized, crystal mounting arrangement apparently exacts penalties in the stability during drive level variations. Many of the feasibility model units had frequency changes of less than 1 part in 10^9 per db change in the drive level (some displayed no detectable change) but the <u>average</u> value was slightly above 1 part in 10^9 per db.

RECOMMENDATION:

A maximum permissible frequency change of ± 1.5 parts in 10^9 per db variation in the drive level over the range from 56 ua to 84 ua is practical.

REQUIREMENT:

3.4.8 <u>Static Capacitance</u>.- Static capacitance shall be 3.5 uufd ± 10%.

COMMENT:

The stringent resistance requirement and the additional capacitance introduced by the ruggedized mounting make it impractical to meet the 3.5 ± 10% uufd requirement. The feasibility model crystal units produced for this project averaged 4.4 uufd static capacitance.

RECOMMENDATION:

A static capacitance requirement of 4.5 uufd ± 10% is recommended.

REQUIREMENT:

3.4.9 Pressure.- The crystal unit shall be capable of operation at an altitude of 100,000 feet without incurring any change in frequency and/or effective resistance to the unit.

COMMENT:

There is no difficulty in meeting this requirement provided the limitations of measurement equipment are considered when the requirement "without incurring any change" is defined for test purposes. It was not possible to make frequency measurements on sample units while in the test chamber because of the problems imposed in placing an oven in the chamber so that measurements could be made at the specified operating conditions. Measurements made "before and after" indicated that no changes occured within the ability of the test equipment to duplicate measurements. In addition, since these units are sealed in high vacuum in glass envelopes, operating at low pressures has no direct effect on them.

RECOMMENDATION:

This is a design requirement, for which testing of production units should not be necessary.

REQUIREMENT:

3.4.10 Seal.- During the test specified, there shall be no evidence of leakage of gas or air from the inside of the crystal unit. Bubbles leaking from the unit as results of pressure test shall be evidence that the crystal unit is not sufficiently sealed for operation at high altitude.

COMMENT:

This test is superfluous on these units; they are sealed in high vacuum in glass envelopes. Leakage does not usually develop in flame sealed glass envelopes without visible signs (cracks or chips) and even if leakage did occur both frequency and activity would be significantly changed by the loss of the vacuum inside the bulb. Any leak large enough to cause visible bubbles would have long since destroyed the usefulness of the unit. However, the possibility of improper seals or excessive strains in the envelope can be effectively located by a glass envelope strain test such as is set forth in MIL-C-3098/49 for the CR-71/U units.

RECOMMENDATION:

The "seal" test and requirement should be eliminated and a "glass envelope strain" test substituted. Sealed units should be immersed in boiling water for 10 seconds and then plunged directly into ice water for 5 seconds. Microscopic examination of the seal for cracks can then be made if desired. Units which pass this thermal shock test will meet the requirements of both the "Pressure" test and the "Seal" test.

REQUIREMENT:

3.4.11 Aging.- Maximum allowable frequency deviation shall be ± 1 part in 10^9 over a period of 48 hours. Measurements over shorter time intervals shall show proportionally smaller deviations.

CONDITIONS:

4.8 Preaging.- Prior to any of the above tests the crystal units shall be subjected to a preaging period of two (2) weeks at a temperature maintained at a constant temperature within ± 0.01°C of the initial temperature...

COMMENT:

None of the sample units produced for this project met the aging requirement. Most changed about 1 part in 10^9 in eight hours and continued to age at this rate for the two week preage period. This performance is considered to be a direct result of the +90°C area operating temperatures although the stiff mounting undoubtedly also contributes to the aging. Even when the two week pre-aging period consists of actual continuous operation instead of temperature control alone it is doubtful if most units can ever attain a consistent stability closer than ± 2 parts in 10^9 per day. (Evidence indicates that significantly better stability can be obtained at lower operating temperatures but sufficient data to permit specific recommendations was not accumulated.)

RECOMMENDATION:

The aging requirement should permit a maximum frequency change of ± 2 parts in 10^9 per day if operating temperatures above +85°C are to be used.

REQUIREMENT:

3.4.12 Orientation.- The maximum allowable frequency deviation from one plane of orientation to any other shall be no greater than ± 1 part in 10^{10}.

TEST:

4.5 Orientation.- The crystal unit, mounted in the oven, shall be orientated so that the plane of the crystal plate is vertical. The crystal shall be slowly rotated 360° in the plane of the crystal plate. During the rotation, the crystal plate shall be variously oriented in a vertical attitude and at 90° either side of vertical. The frequency shall be measured continuously.

COMMENT:

It was not possible to isolate crystal frequency change of ± 1 part in 10^{10} with available equipment: Stability of the reference standard against which measurements were made was not consistently greater than 5 parts in 10^{10}, counter error in reading the stability signal was ± 1 part in 10^{10}, the inevitable disturbances of the crystal-test set leads contributed up to 3 or 4 parts in 10^{10} disturbance, and some additional error apparently results from effects of orientation on the oven itself. It is doubtful if the actual accuracy was greater than 1 part in 10^9 and very few of the sample units displayed frequency changes this great during orientation tests. (These sample units are an improvement over the earlier units in orientation; CR-71/U's are required to hold only 1 part in 10^8 during this test and even CR-(XM-7)/U's hold only 3 or 4 parts in 10^9.)

RECOMMENDATION:

A maximum frequency change of ± 1 part in 10^9 as a result of shifts in orientation is a realistic requirement.

REQUIREMENT:

3.4.13 Vibration.- When units are tested for vibration there shall be no mechanical damage to the unit. The frequency shall not change by more than 1 part in 10^9 when vibrated in accordance with paragraph 4.3 of this exhibit.

CONDITIONS:

4.3 Vibration.- While operating, the crystal units shall be vibrated under the following conditions: The crystal unit, mounted in an oven as furnished by the contractor, shall be rigidly mounted on a vibration machine, in each of the three successive mutually perpendicular planes, one of which is the plane in which the crystal plate is parallel to the vibration table. In each plane, 20 minutes of vibration at 10 to 55 cycles per second shall be applied, followed by 20 minutes at 55 to 1000 cycles per second (total vibration time, 40

minutes in each plane, 2 hours in all planes.) The vibration at 10 to 55 cycles per second shall consist of a simple harmonic motion having a constant amplitude of 0.030 inch (total excursion 0.060 inch.) The frequency of vibration shall be varied uniformly over the range from 10 to 55 cycles per second and returned to 10 cycles per second. This range shall be traversed within 1 minute. The vibration at 55 to 1000 cycles per second shall have a constant acceleration of 10 gravity units. The range from 55 to 1000 cycles per second and return to 55 cycles per second shall be traversed within 1 minute, alternately. The three periods at 10 to 55 cycles per second may precede or follow the three at 55 to 1000 cycles per second. The frequency and resonance resistance of the crystal unit shall be measured continuously during vibration.

COMMENT:

It was possible to monitor stability during vibration only to an accuracy of ± 1 part in 10^9 (± 0.1 cps at 100 mc), since the UHF equipment could not be used. None of the final design sample units changed more than the ± 1 part in 10^9 reading during vibration up to 550 cycles per second at 10G acceleration; however, some units displayed changes up to 2 parts in 10^9 during the 550 cps to 1000 cps vibration. It was not possible to determine performances closer than this.

RECOMMENDATION:

Maximum frequency change during vibration from 10 to 1000 cycles per second at 10G acceleration should be ± 2 parts in 10^9.

REQUIREMENT:

4.4 <u>Sustained Acceleration</u>.- The crystal shall be subjected, for at least three (3) minutes in each of three mutually perpendicular planes, to a sustained acceleration of 10 gravity units. During this test the unit shall operate within frequency tolerances established by 4.11 of this exhibit. (1 part in 10^9)

COMMENT:

It was impossible to perform the specified acceleration test. No centrifuge suitable for this test was available and efforts to locate some other laboratory which could perform the test accurately were not successful. The performance of the feasibility model units under constant acceleration is not known.

REQUIREMENT:

Shock.- No shock test was listed by Exhibit WWRN 61-11.

COMMENT:

The excellent support provided by the four-ribbon crystal mounting arrangement provides unusual ability to withstand shock. The CR-71/U units of MIL-C-3098C are permitted to change frequency ± 1 part in 10^8 as a result of 50G shock; the feasibility model units tested for this project held at least ± 1 part in 10^8 after 100G shock.

RECOMMENDATION:

A maximum permissible frequency change of ± 1 part in 10^8 as a result of shock testing per Method 202 of MIL-STD 202B, 100G acceleration and 11 millisecond duration, is realistic.

VII. RECOMMENDED SPECIFICATION

1. Scope

   The following specification is intended only to outline realistic requirements for high precision crystal units of the type described by WWRN 61-11. These requirements can be met, with reasonable yields, by units which utilize the design described in this report.

2. Applicable Documents

   The following documents are intended to supplement this specification:

Military:	MIL-C-3098C	Crystal Units, Quartz
	MIL-H-10056	Holders, Crystal
Standards:	MIL-STD-202B	Test Methods for Electrical and Electronic Component Parts
Manuals:	MA-7190	Radio Frequency Laboratories (RFL) Instruction Manual for Test Set AN/TSM-17

3. Design Requirements

   3.1 Crystal Holder - Type HC-30/U per MIL-H-10056/12

   3.2 Insulation Resistance - Not less than 500 megohms lead-to-lead

   3.3 Mode of Operation - Fifth overtone mode

   3.4 Test Set - AN/TSM-17

   3.5 Drive Level - 70 ua ± 20%

   3.6 Static Capacitance - 4.5 ± 10% pfd.

4. Performance Requirements

   4.1 Frequency - Units shall operate at anti-resonance into a load capacitance of 32.0 ± 0.5 pfd. Nominal frequency shall be five megacycles.

4.2 Tolerance on Nominal Frequency - ± 5 parts in 10^7 at operating temperature.

4.3 Operating Temperature - The point of zero temperature coefficient, as determined individually for each unit and marked on the top of the unit. The operating temperature shall be within +90°±2°C.

4.4 Resonance Resistance - 175 ohms maximum, 100 ohms minimum, at operating temperature.

4.5 Frequency Change Due to Drive Level Variations - No greater than ± 1.5 parts in 10^9 per 1 db change over the range 56 ua to 84 ua.

4.6 Shock - Maximum of ± 1 part in 10^8 frequency change and ± 10% resistance change as a result of the test listed by 5.2.

4.7 Vibration - Maximum of ± 2 parts in 10^9 frequency change and ± 10% resistance change as a result of the test listed by 5.3.

4.8 Orientation - Maximum of ± 1 part in 10^9 frequency change as a result of a change in orientation from any plane to any other plane.

4.9 Aging - Maximum of ± 2 parts in 10^9 frequency change per day after 14 days of continuous operation.

5. Test Details

5.1 Conditions - All tests shall be made with the units operating within 0.5°C of the individual operating temperatures as marked on the units. Temperature control of at least 0.01°C must be maintained.

5.2 Shock Test - Per MIL-STD-202B, Method 202A. Unit mounted in oven, at operating temperature. Three blows (one in each of three mutually perpendicular planes), 100G, 11 milliseconds duration. Measurements made before and after test.

5.3 Vibration - Units shall be mounted in an oven at operating temperature and operated during the test. Frequency shall be recorded continuously during the test and resistance checked before and after the test. Vibration shall be 10 cps to 1,000 cps, at 10 G acceleration. The vibration range shall be divided into three sections, such as 10 to 55, 55 to 550, and 550 to 1,000 cps. A full sweep and return cycle in each section shall take approximately one minute. Test shall consist of 20 minutes per plane for each section of the range. (Total of three hours.)

TABLE III

CAPSULE COMPARISON

5 MC HIGH PRECISION CRYSTAL UNITS

Note: Information shown is oversimplified to facilitate presentation; see governing specifications for actual requirements.

REQUIREMENT	CR-71/U (MIL-C-3098/49)	CR-(XM-7)/U (CAPABILITIES)	BLILEY'S REC. SPEC.	WWRN 61-11 REQUIREMENTS
HOLDER	HC-30/U	SAME	SAME	SAME
MODE	FIFTH	SAME	SAME	SAME
CONTOUR	PLANO-CONVEX	PLANO-CONVEX	BI-CONVEX	----
TOLERANCE	$\pm 8 \times 10^{-7}$	$\pm 8 \times 10^{-7}$	$\pm 5 \times 10^{-7}$	$\pm 1 \times 10^{-8}$
TEST SET	AN/TSM-17	SAME	SAME	----
LOAD CAPACITANCE	32 uuf	SAME	SAME	SAME
DRIVE LEVEL	70 ua ± 20%	SAME	SAME	SAME
RESISTANCE	175 OHMS MAX. 100 OHMS MIN.	SAME	SAME	SAME
STATIC CAPACITANCE	4.0 pf ± 10%	4.0 pf ± 10%	4.5 pf ± 10%	3.5 pf ± 10%
OPERATING TEMPERATURE	71°C AREA (± 6°C)	71°C AREA (± 6°C)	NOT ABOVE 85°C (± 4°C tolerance)	90°C AREA (± 2°C)

CAPSULE COMPARISON (CON'T)

5 MC HIGH PRECISION CRYSTAL UNITS

REQUIREMENT	CR-71/U (MIL-C-3098/49)	CR-(XM-7)/U (CAPABILITIES)	BLILEY'S REC. SPEC.	WWRN 61-11 REQUIREMENTS
SHOCK TEST	3 blows, 50G 7 millisec	3 blows, 50G 7 millisec	3 blows, 100G 11 millisec	NONE
REQ.	±1 x 10^{-8}	±5 x 10^{-9}	±5 x 10^{-9}	NONE
VIBRATION TEST	10-150 cps, 10G	10-550 cps, 10G	10-1000 cps, 10G	10-1000 cps, 10G
REQ.	±1 x 10^{-7}	±1 x 10^{-7}	±2 x 10^{-9}	±1 x 10^{-9}
ORIENTATION TEST	CHANGE TO ANY OTHER ATTITUDE	SAME	SAME	SAME
REQ.	±1 x 10^{-8}	±5 x 10^{-9}	±1 x 10^{-9}	±1 x 10^{-10}
AGING TEST REQ.	AFTER 12 DAYS ±5 x 10^{-9}/ 9 days	AFTER 12 DAYS ±5 x 10^{-9}/ 9 days	AFTER 14 DAYS ±2 x 10^{-9}/ 24 hrs.	AFTER 14 DAYS ±1 x 10^{-9}/ 48 hrs.
ACCELERATION TEST	NONE	NONE	NOT KNOWN	10G, 3 minutes
REQ.	NONE	NONE	NOT KNOWN	±1 x 10^{-9}

VIII. CONCLUSIONS

Although it is not feasible to produce high precision quartz crystal units which meet all of the requirements listed by WADD Exhibit WWRN 61-11 it is possible to meet many of these requirements and to approach most of the others much more closely than would be expected from study of conventional high precision units.

Specific recommendations for maximum realistic requirements attainable at the present time are presented in this report. These requirements, which can be met by units which use the design described, show that significantly better performances have been achieved in shock, vibration, and orientation tests than were previously possible.

Further advancement in state-of-art techniques for ruggedized high precision crystal units is hindered by lack of test equipment which will determine crystal performances accurately. It is doubtful if additional development of ruggedized high precision crystal units can be accomplished until better ovens, more stable reference standards, and more accurate frequency measurement equipment are all available.

RECOMMENDATIONS

A recommended specification has been presented in this report to outline the maximum realistic requirements for ruggedized high precision crystal units of the type described by WADD Exhibit WWRN 61-11. In addition to this specification the following recommendations are made:

1. It is recommended that the maximum operating temperature for units of this type be +85°C and that lower temperatures (+75°C area) be used wherever possible. (Definite penalties in performances and yields result from use of the higher temperatures.)

2. It is recommended that procurement specifications not require a higher degree of ruggedization than is necessary for the intended application. (The ruggedized mounts are difficult to fabricate and will be expensive in both time and money. In addition, there are definite penalities in aging stability as a result of the stiffer mount, probably due to the additional strains which are imposed on the crystal.)

3. It is also recommended that attention be given to further development of test equipment so that the true performances of available high precision crystal units may be accurately ascertained. (Present equipment is not capable of measurements of sufficient accuracy; many of the recommended maximum realistic requirements have been set by lack of ability to measure rather than by crystal performance limitations.)

IX. REFERENCES

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Smith, W.L., An Ultra-Precise Standard of Frequency: Final Report. Bell Telephone Laboratories for U.S. Army Signal Research and Development Laboratories, Fort Monmouth, N.J. Contract DA-36-039-SC-73078. December 1960.

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B. Manuals

MA-7190, Manual of Instruction for RFL Model 991, 5 Mc High Precision Crystal Test Set (AN/TSM-17). Radio Frequency Laboratories, Inc., Boonton, N.J.

C. Military Specifications

MIL-C-3098C	Crystal Units, Quartz, General Specification for
MIL-H-10056	Holders, Crystal, General Specification for
MIL-STD-202B	Test Methods for Electronic and Electrical Component Parts

Aeronautical Systems Division, Dir/ Avionics, Electromagnetic Warfare and Communications Lab, Wright-Patterson AFB, Ohio.
Rpt No. ASD-TDR-62-1054. RUGGEDIZED PRECISION CRYSTAL UNIT FOR AIRBORNE AND MISSILEBORNE FREQUENCY SOURCES. Final Report, May 63, 39p. incl illus tables, 3 refs.

Unclassified Report

Investigation was made of the feasibility of requirements which had been set up to guide development of rugged, high-precision crystals for

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2. Piezoelectric materials
3. Crystals

I. AFSC Project 4156, Task 415606
II. Contract AF33 (616)-8100
III. Bliley Electric Co., Erie, Pa.
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V. Aval fr OTS
VI. In ASTIA collection

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UNCLASSIFIED

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Aeronautical Systems Division, Dir/ Avionics, Electromagnetic Warfare and Communications Lab, Wright-Patterson AFB, Ohio.
Rpt No. ASD-TDR-62-1054. RUGGEDIZED PRECISION CRYSTAL UNIT FOR AIRBORNE AND MISSILEBORNE FREQUENCY SOURCES. Final Report, May 63, 39p. incl illus tables, 3 refs.

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